Defect Prediction in Composites Based on Numerical Simulation and Expertise Knowledge

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Abstract

Advanced composites components for aircraft application continues to rise and primary structures are increasingly made from advanced composites. The quality and its stability of the composites structure are very important. As we known, the composites structure is formed together with the composite material. The material, processes and design practices that are used to generate the composite structure will affect the quality. It is necessary to develop a method being able to previously predict the defect in the composites and to improve the quality of the composites material. In this paper, based on the numerical simulation module (temperature and pressure field prediction including the auxiliary material and composites) and expertise knowledge i.e. combined with statistical results and defect micrographs, the strong correlation between geometric characteristics (for instance, thickness, curvature radius) in composite components and controllability of manufacturing defects was obtained, the void defect can be predicted for the L-shaped laminates. These results can provide a good reference for the processor and designer, and are very helpful for the improvement and quality control of composite parts.

1 Introduction

Advanced composites are commonly used as structural components in aircraft, aerospace, and automotive industries. Autoclave molding technology is one of the most popular techniques for these materials. However, during the manufacturing process of composites components, various defects such as void, delamination and debonding, etc., inevitably appear as results of curing schedule, environment, raw materials, and unreasonable structure design of composite components. These manufacturing defects sometimes cause serious threat to mechanical properties and service life of composites, paralleled with making a great economic loss. Exploring the causes and controlled methods of defects in composites has attracted increasing consideration over the past few decades.

The types of composite components applied to aircraft are different and complex; therefore, the resin flow of composite components is much more complicated because of the complexity of temperature distribution and pressure transfer in components. In more detail, the ratio of defect appearance would increase and the controllability of such defects would also become difficult when some structure parameters exceed a certain range.

In this paper, Numerical models were developed and simulations were conducted for composites to study the temperature and pressure in the laminates during the cure process. Combined with the model of pore growth and the expertise knowledge (experimental data), the probability of generation of pore in the laminate can be predicted. These results can provide a good reference for the processor and designer, and are very helpful for the improvement and quality control of composite parts.

2 Process Model

2.1 Temperature Field

For the heat transfer in composites during the autoclave process, the governing equations combined the heat transfer and resin reaction kinetics is established, which is responsible for calculation of the distribution of component temperature and the cure degree of resin. For the two-dimensional case, and with the coordinate axes aligned with the material principal axes, heat transfer equation can be written as:

$$\rho C_{\mathrm{p}} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{xx}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial T}{\partial z}\right) + \rho_{\mathrm{R}}\dot{H} \qquad (1)$$

Where T is the temperature, t is the time; ρ and C_{p} are the composite density and specific heat capacity, respectively. k_{xx} and k_{zz} are the thermal conductivities, ρ_{R} is the resin density, $\dot{H}$ is the rate of heat generation of the resin exothermic reaction. Coordinate z refers to the thickness direction of the laminate while x refers to the length direction. At each step, a variety of equations are used to calculate the composite thermo-physical properties in Eq.1 from the local fiber volume fraction, and instantaneous resin and fiber properties.

The rate of heat generation in Eq.1 can be determined from:

$$\dot{H} = H_{\mathrm{u}} \frac{da}{dt} = H_{\mathrm{u}} f(T, \alpha) \tag{2}$$

Where H_u is the total amount of heat generated during a ‘complete’ resin reaction, a is the degree of cure, da/dt is cure rate and is a function of temperature T and degree of cure a.

For the tool and auxiliary materials, the Fourier heat transfer model is used, the material property parameters including thermal conductivity, heat specific, density obtained by experiments.

2.2 Pressure Field

The squeezed sponge model was employed to describe the resin flow and fiber compaction behavior in composite. The composite material is assumed to be an elastic, deformable, porous medium in which the resin flows relative to the fiber bed obeying Darcy’s law. For the representative element, the differential equilibrium equation can be written as:

$$\frac{\partial \sigma_{\mathrm{ij}}}{\partial x_{\mathrm{j}}} + \frac{\partial P}{\partial x_{\mathrm{i}}} = 0 \tag{3}$$

Where σ_{ij} and P are the fiber effective stress and resin pressure, respectively. Subscript *i* and *j* stand for Cartesian coordinates *x* or *z*.

According to the mass conservation, the flow continuity equation is expressed as:

$$\frac{\partial \varepsilon_{\mathrm{v}}}{\partial t} = \frac{\partial}{\partial x}\left(\frac{S_{\mathrm{xx}}}{\mu}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{S_{\mathrm{zz}}}{\mu}\frac{\partial P}{\partial z}\right) \tag{4}$$

Where S_{xx}, S_{zz} are the fiber bed permeability which varies with varying fiber volume fraction, μ is resin viscosity, ε_v is the bulk strain.

The simplified constitutive equation [3, 11-12] is

$$\begin{aligned} \sigma_{\mathrm{xx}} &= E_{\mathrm{xx}} \varepsilon_{\mathrm{xx}} \\ \sigma_{\mathrm{zz}} &= A\mathrm{s} \cdot \left(1 - \sqrt{V_{\mathrm{f}} / V_0}\right) \Big/ \left(\sqrt{V_{\mathrm{a}} / V_{\mathrm{f}}} - 1\right)^4 \\ \tau_{\mathrm{xz}} &= G_{\mathrm{xz}} \gamma_{\mathrm{xz}} \end{aligned} \tag{5}$$

where E_{xx}, E_{zz} and G_{xz} are the fiber bundle elastic constants, ε_{xx}, ε_{zz} and γ_{xz} are the strains, V_f is the fiber volume fraction, V_a is the maximum available fiber volume fraction, V_0 is the initial fiber volume fraction, As is a spring constant.

The finite element formulations and validations of the flow-compaction model can be found in Ref. [2]. Resin viscosity, fiber bed permeability and fiber volume fraction are updated at each time step in the solution.

3 Manufacturing Defects in Autoclave Molding

In reference [3], the manufacturing defects were summarized systematically according to the results of non-destructive identification such as ultrasonic and X-ray, in which some defects of fiber waviness, fiber volume fraction non uniformity, and thickness non-uniformity were not included in the statistical range.

The main defects often formed in autoclave molding and the defect ratio between the number of every type of defects and the number of total defects are presented in Figure 1.

The statistical data sample for various types of manufacturing defects distributed in every composite component is listed in table 1.

In Fig.1 and Table 1, D1, D2, D3, D4, D5, D6, D7, and D8 refers to delamination, void, pore, debonding, rich resin, lack resin, loose, and deformation, respectively.A1 and A2 in Table 1 represent the total number of components with defects and total number of components.

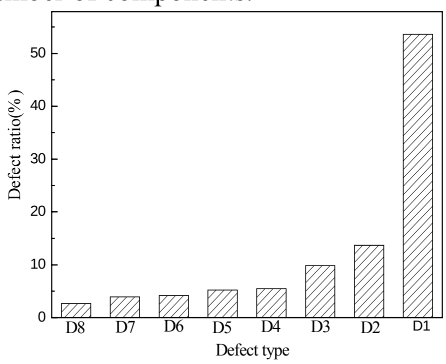


Fig.1 Contrast graph for manufacturing defects

Table1. Statistical data sample of manufacturing defects in composite components

Defects components	D1	D2	D3	D4	D5	D6	D7	D8	A1	A2
Uniformity thickness laminates	2	17	1	–	–	–	–	–	20	467
Non-uniformity thickness laminates	35	9	16	–	23	–	–	1	84	1461
L-shape laminates	3	23	–	–	–	2	–	15	43	2947
U-shape laminates	46	18	14	–	2	2	15	4	101	813
Box-shape laminates	261	31	42	–	8	12	4	4	362	3995
I-shape laminates	86	12	8	–	6	20	18	–	150	634
Bonding structure	59	18	11	61	12	13	–	1	175	1835
Total number	492	128	92	61	51	49	37	25	935	12912

From Fig.1, obviously, delamination occupies a dominant position among the manufacturing defects; pore and void are also two important defects of which ratios are much lower than delamination ratio but higher than the other defect ratios.

Curvature radius is a typical geometric characteristic of composite components, which are widely applied in beams, webs, and stiffened plates. The effect of different curvature radius on manufacturing defects and contrast for defect types in the curve zone are shown in Fig.2 and Fig.3, respectively. It can be seen from Fig.2 that the defect ratio gradually decreases and the controllability of these defects increases with increasing the curvature radius of components. From Fig.3, the maximum ratio of defects in curve zone is delamination, the second maximum ratio of defects is void and loose, and the effect of curvature radius on rich resin and lack resin is the weakest. Fig.4 showed the metallograph of void in the corner region.

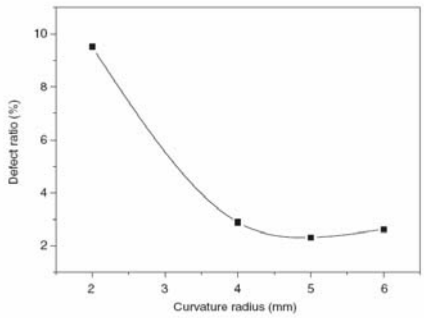


Fig2. Effect of curvature radius on manufacturing defects

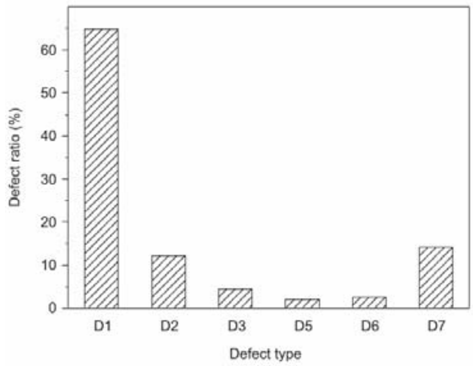


Fig3. Contrast graph for various defects in curve zone

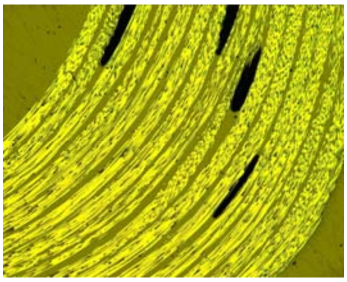


Fig4. Void defect in the corner

4 Defects prediction in L-shaped Composites

From the experimental result, voids are one of the main types of manufacturing defects, while the negative impact of voids on laminates has been largely studied, and it has been shown that voids can promote damages, crack initiation and propagation and these defects generate important mechanical property decreases like interlaminar shear stress, tensile strengths, and modulus of elasticity [4, 5]. Therefore, it is mandatory to minimize the occurrence and growth of these porosities in composite laminates, phenomenon that can be directly linked to manufacturing process.

The mainly source of voids can summarized as air entrapped in the lay-up assembly and volatile small molecule such as water and dissolvent in the resin. While the temperatures, resin pressure, vapour pressure in the pore, the time of pressure application and gel time are the main factors effecting the void formation, growth and inhibiting.

According to Raoult's law, for the acetone in the resin solution, we can get the model of pore formulation as:

$$P_r \ge P_{\min} = 5.12\times10^3 \exp\left(\frac{-3568}{T}\right)X_0 \qquad (6)$$

In which, P_r is resin pressure; $P_{\min}$ is the minimum pressure to inhibiting the growth of pore; X_0 is mole fraction of acetone in the resin.

Based on the GPC method, with the molecular weight of resin, acetone, resin volume fraction and volatile content, the mole fraction of acetone in the resin solution can be calculated.

For the air entrapped in the lay-up, the following model is gotten to describe the pore growth.

$$P_r \ge P_{\min} = 5.84\times10^2 \exp\left(\frac{-3568}{T}\right) + 3.41\times10^{-4}T - 0.10 \qquad (7)$$

With the numerical simulation models, the temperature and pressure in the composite laminates can be predicted, combined with the model of pore growth and the expertise knowledge (experimental data), the probability of generation of pore in the laminate can be predicted.

FEA method and self-developed program are developed to solve the numerical simulation models and predict the temperature and pressure distribution in the composite laminates during the curing process. With the numerical models, the material properties i.e. material systems, lay-up type, cure cycles (temperature, pressure, and the time of pressure application) and structure parameters (thickness, radiu, etc.) can be studied. It is an effective method to predict the defects produced in the curing process.

4.1 temperature prediction

Firstly, based on the heat transfer models, the effect of rubber mould on heat transfer was studied with the configuration as shown in Fig.5 including the aluminum tool, the L-shaped lay-up, bleeder materials and rubber mould. All the boundaries are set as the convective boundary with h=130W/m^2·K.

The gas temperature in the autoclave was increased from room temperature to 120 ℃ and then the temperature was held for 10min. After that, the temperature was raised to 190℃ and then kept at this temperature for 30min. Fig.6 was the temperature difference between the typical points in the lay-up assembly including the auxiliary materials. During the cure cycle, the maximum temperature difference is about 9℃ in the rubber mould and 3℃ in the lay-up, respectively. According to the simulated results, for the thin laminates, the temperature distribution is uniform and the effect of temperature difference on the consolidation process can be ignored in the following study.

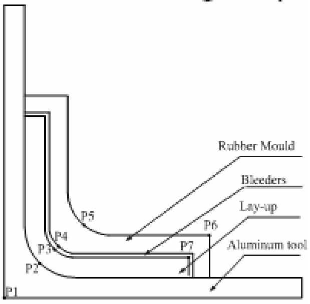
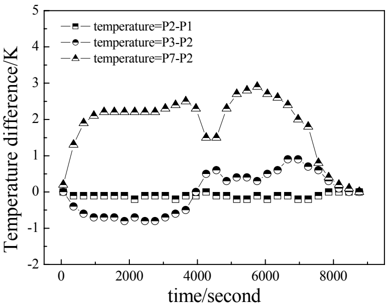
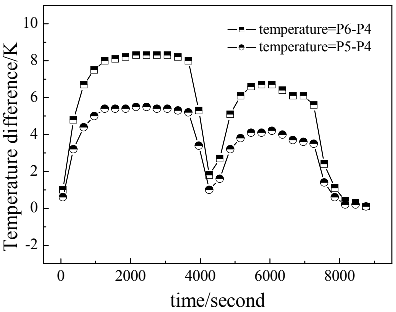


Fig.5 Schematic for heat transfer analysis



(a) Temperature difference in the lay-up



(b) Temperature difference in the rubber mould

Fig.6 temperature difference between the typical points

4.2 pressure prediction

Fig. 7 shows a schematic of manufacturing an L-shaped laminate. In this study, the influence of tool-part interaction on the pressure transfer of tools and the consolidation process of laminates before resin gelation are considered in the numerical model. Fig.8. 4-node elements were used for the whole model. The symmetrical arm lengths of L-shaped laminate and metal die were 50mm and 80mm, respectively.

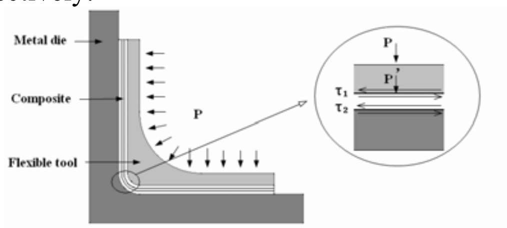


Fig. 7 Schematic of manufacturing an L-shaped laminate and a sliding interface condition occurs at the tool-part interfaces

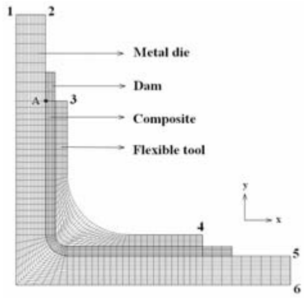
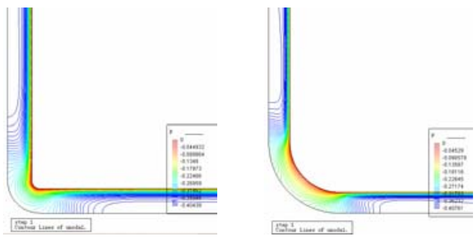


Fig. 8 Geometry and mesh for the simulation

Fig. 9 shows the resin pressure distribution in the laminates, with the different radius. From the results, we can find that the resin pressure in the corner region is much lower than the one in the flat part and the smaller the radius is, lower is the resin pressure in the corner. The regular is similar to the experimental results. Base on the simulation mode, the model of pore growth and expertise knowledge, probability distribution of void in the laminate can be predicted in Fig.10. The pore is easier to formulate in the corner, which is corresponding to the experimental data and approve the valuation of prediction method of defects.



(a) R=4mm (b) R=10mm

Fig. 9 Resin pressure distribution

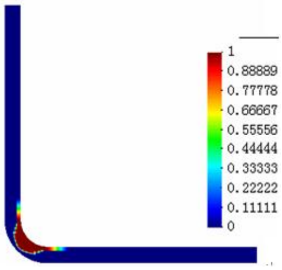


Fig.10 Predicted probability distribution of void

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